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DYNAMIC ANALYSIS OF BANGALORE UNDERGROUND METRO TUNNELS BY NUMERICAL SIMULATION

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ABSTRACT

With buildings roads and railways occupying most spaces in cities, there is a constant increase in traffic congestion and pollution. An underground express-way/metro tunnel below such central business districts serves as an effective sustainable option. Along with longer service life, they can optimize the energy usage, minimize CO_2 emissions, reduce carbon footprint and thus co-exist as an integral part of a sustainable infrastructure system. In this paper, we address the challenge of analyzing one such Underground metro tunnel in Bangalore. The paper highlights the elastic and elasto-plastic analysis of the twin tunnel system subjected to gravity, hydrostatic pressure conditions combined with blast induced pressures. The intention is to study the blast effects of a terror-attack on the tunnel system, by simulating a pressure wave and study the effects on neighboring tunnels for various time instances. This geotechnical and structural modeling along with its analysis are carried out using ANSYS. The validation of the results with Kirsch and Bray's solutions is the back bone of this numerical model. Further, plane-strain analysis is done to study the effects of various shapes of tunnels under such loads, by comparing the responses of single and twin, with and without support systems.

KEYWORDS: Underground Metro Tunnel, ANSYS, Numerical Simulation, Blasting Effects, Elasto-Plastic Analysis

INTRODUCTION

The main objective of this paper is to develop a numerical Finite element model that reflects the exact field conditions of the Underground Metro Tunnel in order to study its resilience and sustainability with various kinds of loads. An underground structure in a crowded urban area implies that the modification on the natural habitat above ground level is minimal. This enables effective and economical means of transportation with reduced fuel consumption and pollution, enhancing human health aspects by reducing vehicle exhaust and green house gases. Numerical analysis helps in understanding stresses & deformations in an underground tunnel by modeling and simulating exact field parameters. A detail study of the complexity in soil modeling and non-linear behavior of tunnel is required. To serve this purpose, suitable literature references are studied and validated as a prerequisite.

Salient Features of Bangalore Underground Metro Tunnel

A study with BMRCL revealed the following salient features of metro tunnel:

- The total length of the Bangalore metro line is 42.3 kms, which is divided into two corridors. The first one runs along the east – west corridor extending up to 18.1 kms and the other running along the north-south corridor is 24.2 kms long
- The focus of this study is confined to the underground section with a twin tunnel for a length of 4.8 kms along the

east-west section (See Figure 1)

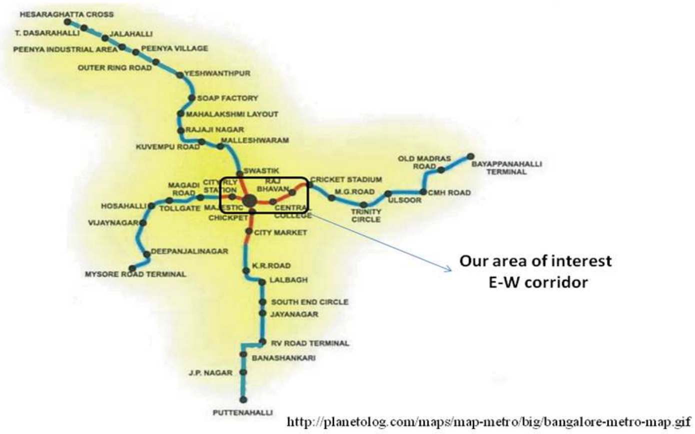


Figure 1: Alignment/Routes of Bangalore Metro Including Underground Section

- Tunnels are bored using slurry TBM with an inner diameter of 5.6 m which is reinforced with a concrete lining of thickness 280 mm
- The depth of the tunnel from the ground level is approximately 15 to 18.3m below the surface of the ground, the twin tunnel centers are 15.04 m apart from each other (Figure 2)
- With a capacity of 11m per day, Helen and Margarita are the two drilling machines (Tunnel Boring Machines, TBM) used for tunneling this section. The earth pressure balanced TBM method has been employed for tunneling using slurry TBM, while the cut and cover method facilitated the stations

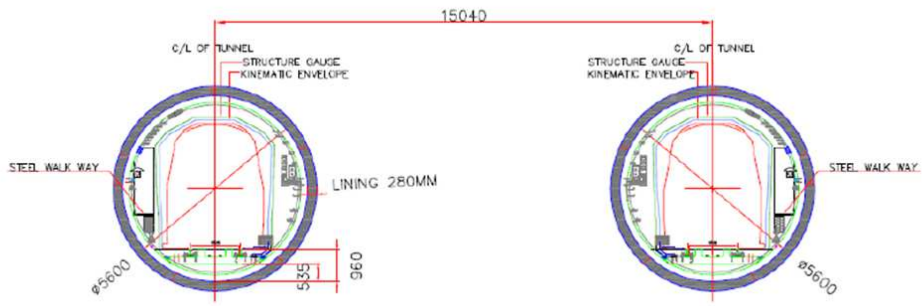


Figure 2: Cross-Section of Bangalore Metro Underground Tunnel (Sudhir Chandra, 2013)

MATERIALS AND METHODS

The key elements that help us to quantify the induced damage on underground tunnels due to the explosion are as follows:

- Self-weight
- Excess water pressure in the soil
- Blast pressure characteristics
- Weight of the TNT used

- Soil strata available
- Soil bearing and shock absorption capacity

Further, the complexity of this problem is determined by various parameters such as the dynamic ground-structure interaction. Fluid–structure interaction, non-linear response of ground media, three dimensional effects and structural damage add to this list. However, in our study, we concentrate on adopting elastic and non linear properties in the numerical model to study various static and blast loads only.

Soil /Rock Properties of East-West section

The properties such as Young's modulus, Poisson's ratio, and density, for the different layers of soil in Bangalore, along with their depths, are collected from the geotechnical reports of the study area and tabulated as shown in Table 1 below. Some of the elastic properties are taken from Sitharam and Anbazhagan (2008) based on Multichannel analysis of surface waves (MASW) survey.

Table 1: Soil Profile of Bangalore Metro Tunnel

Layers and its Depth (M)	Density (Kg/M^3)	Young's Modulus (N/M^2)	Poisson Ratio	Cohesion (Kpa)	Friction Angle (Deg)
Clayey sand 0 to 3.2m	2000	$3.25x10^{11}$	0.3	5	35
Clayey sand+Gravel 3.2 to 8m	1900	$1.11x10^{11}$	0.3	20	30
Silty sand+Gravel 8 to 28.5m	2000	$4.08x10^{11}$	0.3	15	35
Hard rock > 28.5	2000	$5.23x10^{11}$	0.2	4000	42

Geometry and Boundary Conditions

While considering the size of the numerical model, different values for the dimension of the tunnel system were evaluated based on various factors. If "d" represents the diameter of the tunnel, which is 6.44m, then 2.5d, 3d and 4d represented the options for the geometry of the problem. Figure 3 shows the tunnel grid with the finite element mesh. The influence of stress region exceeds the model boundary in case of 2.5d while the modeling becomes complex to solve in case of 4d. Therefore the optimum dimension is considered as 3 times the diameter on all sides. During the model generation, the bottom end of the tunnel is fixed, while the sides and faces are provided with roller support.

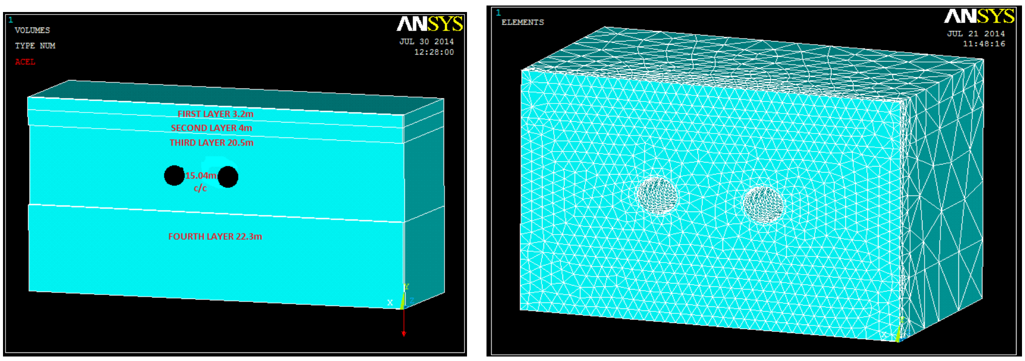


Figure 3: Tunnel Grid with Finite Element Mesh

However, continuing the study with the above dimension, the results obtained displayed reflection of stresses due to short boundary conditions. In order to simulate real-world conditions, dimension in all directions was considered as 100m, thus allowing the soil to absorb all the stress propagation along the tunnel-soil system.

VALIDATION OF ANSYS v.14 FOR ELASTIC AND ELASTO-PLASTIC ANALYSIS

In order to validate the accuracy of results derived from ANSYS, and to determine its coherence with existing work, example problems were considered and elastic and elasto-plastic analysis was carried out as follows.

Validation for Elastic Analysis

A homogenous rectangular plane with a hole, defined as a plane 42 element in ANSYS, is considered for the analysis. The dimension and material properties adopted are as shown in the Table 2 below. Results from ANSYS are compared with the theory proposed by Kirsch solution (Kirsch, 1898). Roller support is provided on the left and bottom faces, while the other two sides are subjected to loads. The radial/tangential stress graph obtained from ANSYS and Kirsch solutions are compared as shown below in Figure 4. The superimposition of the graphs validates this elastic analysis in ANSYS.

Table 2: Material Properties Used for the Validation

Dimension	Hole Radius	Density	Poisson's Ratio	Young's Modulus
200x100 mm	10 mm	1900 kg/m^3	0.3	10,000 MN/mm^2

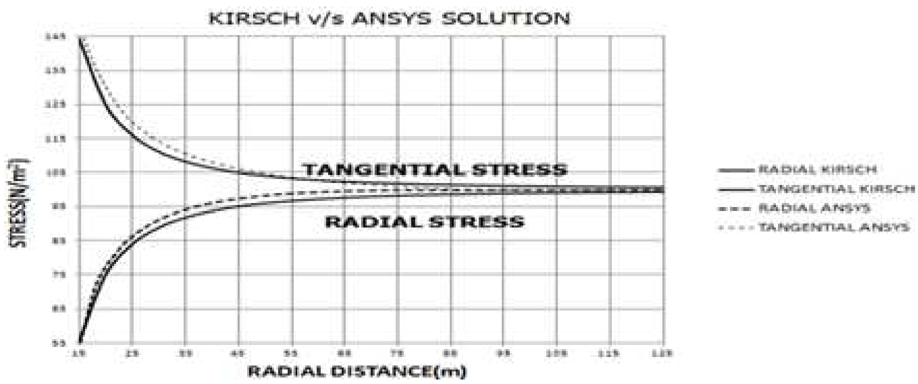


Figure 4: Graphical Comparison of the Results from Kirsch's Solution Vs. ANSYS

Validation for Elasto-Plastic Analysis

A 5m square plane with a hole of 0.5 m radius, defined as a plane 42 element in ANSYS, was evaluated and compared. Formation of both elastic and plastic zone occurs when the stress developed exceeds the yield strength. Using the Drucker - Prager model in ANSYS, the results were compared with solutions obtained from the theoretical model propositions of Bray solution (Bray, 1967). The properties of the material were modeled as given in Table 3 below:

Table 3: Material Properties for the Validation

Young's Modulus	Poisson's Ratio	Density	Angle of Internal Friction	Cohesion	Dilatancy Angle
10,000 MN/mm^2	0.25	1900 kg/m^3	30^0	3.45 MPa	0^0

This graphical comparison shown in Figure 5 verifies the capability of the finite element tool and confirms that the Drucker - Prager model in ANSYS is an appropriate tool to analyze the elastic and plastic stresses and model the deformations. The deviation observed is attributed to the difference in choices, with respect to initial plasticity zone, and meshing adopted for the finite element model.

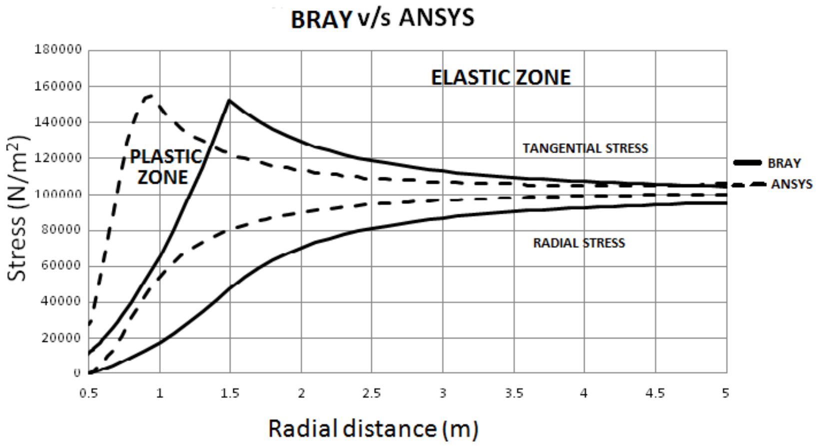


Figure 5: Graphical Comparison of the Results from Bray's Solution vs. ANSYS

Validation of the Software for Blast Analysis

For the purpose of numerical validation, a twin tunnel in New York, similar to the one in Bangalore is selected, and a finite element model was developed using ANSYS. The geometry of this model is described in the Table 4 below:

Table 4: Dimensions of the New York Reference Tunnel

Burial Depth	Inner Diameter	Distance Between the Centers	Extent Along the Longitude	Length	Height
9m	5m	8m	50m	100m	50m

As per the reference study (Huabei Liu, 2009), the soil considered had a unit weight of 18.9KN/m^3. This tunnel was supported with a cast iron lining having a Young's modulus of 1.4e5 MPa. Its Poisson's ratio was given to be 0.2. Huabei Liu (2009) adopted ABAQUS program and used TNT weights to induce blast pressures at various sections within the tunnel. Variation of pressure with time was studied on the first 1m section of the tunnel due to a 50Kg TNT blast inside the tunnel at its centre. From the pressure-time graph, the pressures at various time instances as shown in Table 5 is obtained and is used in the ANSYS validation Model.

Table 5: 50 Kg TNT Pressure Variation with Time

Time in Seconds	0.005	0.009	0.01	0.013	0.058
Pressure in Mpa	3.33	6.67	10	9	7.5

Von-mises stress was the key parameter used to compare the accuracy of the Software and the conditions adopted in the numerical validation of such problems. The Stress-Time Graph derived from ABAQUS as described in the reference paper is superimposed with the graph derived using ANSYS. Figure 6 below shows that the numerical model developed using the finite element tool under discussion has the capability to reproduce the condition.

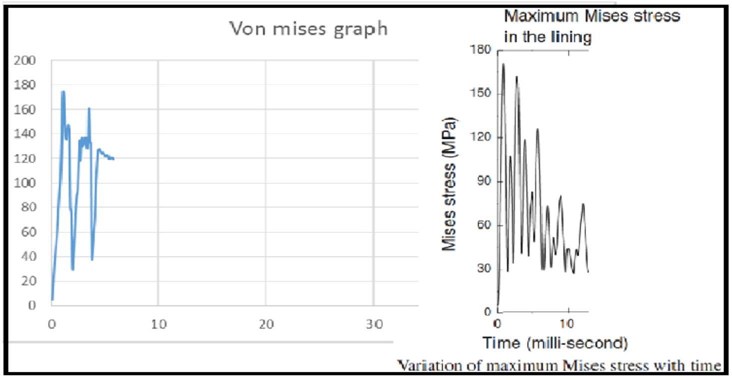


Figure 6: Von Mises Graph Obtained from ANSYS in Comparison with Reference

ANALYSIS OF UNDERGROUND TWIN TUNNEL FOR BLAST INDUCED DAMAGE

The tunnel is considered as a long cylinder in an infinite medium of soil mass in 3D. In order to conduct elastic analysis, the numerical finite element model is built by defining elastic properties like Young's modulus, Poisson's ratio and density of the soil layers as shown in Table 1. Once the elastic analysis is completed, non-linearity is simulated with the help of Drucker - Prager model in ANSYS to conduct elasto-plastic analysis. Here, properties such as cohesion and angle of friction along with the elastic properties are defined to the soil layers, as given in Table 1. Quad free meshing with smart size set to three is the optimum setting used for both the analyses. SOLID65 element type is adopted for 3D modeling which has eight nodes with 3 degrees of freedom at each node.

Static Analysis

Gravity (9.81m/s^2) is applied globally on the model, while the two layers of soil below 5m from the ground level are subjected to 29.43KN/m^3 and 166.67KN/m^3 of pressure respectively, due to water or moisture in the soil (Sekhar & Mohan, 2009). The final layer lies below the tunnel and thus does not influence any such pressure. A 280 mm thick concrete lining is provided with a young's modulus of 3X10^{10}N/m^2 and a Poisson's ratio of 0.2. The comparison of results as shown in Table 6 below reinforces the importance of water content in the soil. The stresses induced due to such pressures are prominent and its consideration becomes vital in analyzing the tunnel system.

Table 6: Comparison of Elastic & Elasto-Plastic Analysis with Static Loads

Results for 3D Fully Bored Twin Tunnel with Lining (30m Section)		Gravity	Gravity + Hydrostatic
Max. Displacement (m)	Elastic	0.680X10^{-6}	0.126X10^{-4}
	Elasto Plastic	0.671X10^{-6}	0.150X10^{-4}
Max. Radial stress (N/m^2)	Elastic	18794.8	140827
	Elasto Plastic	3812.86	87888.9
Max. Tangential stress (N/m^2)	Elastic	9027.38	511462
	Elasto Plastic	3699.42	87293.8
Max. Stress intensity (N/m^2)	Elastic	30256.8	385477
	Elasto Plastic	16493	448020

Drucker-Prager model in ANSYS is used to analyze the elastic and plastic stresses and model the deformations. The following images in Figure 7 display the displacement and stresses experienced in the tunnel due to the above mentioned static loads.

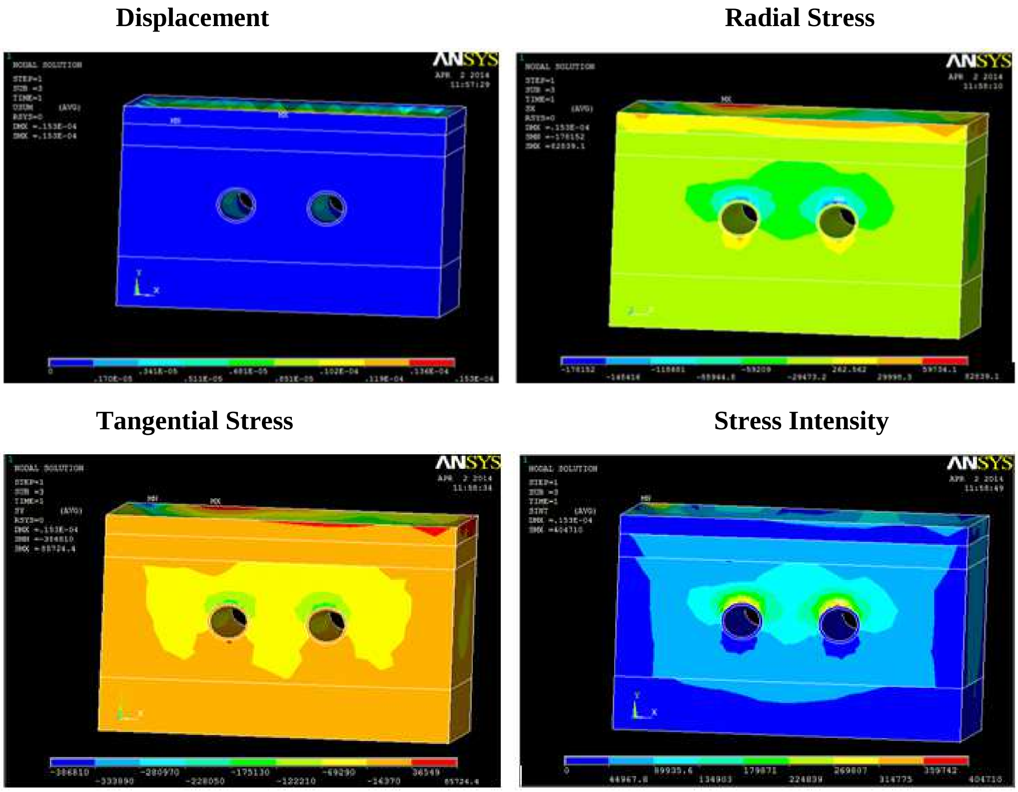


Figure 7: Displacement, Radial Stress, Tangential Stress and Stress Intensity Images for Twin Tunnel With Lining From Elasto-Plastic Analysis

Blast Analysis

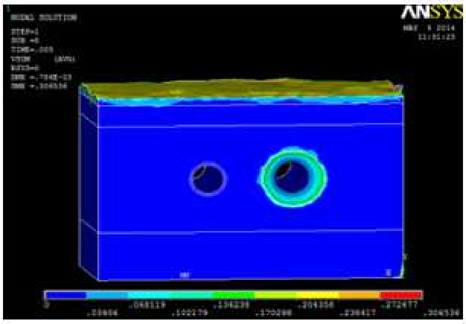
The impact of TNT blast on underground structures using transient analysis in ANSYS is studied for 30kg TNT along with static in-situ stresses. The time loads are specified in separate LS files and solved together. Analysis includes both positive and suction phase, but the latter is not accounted here. The blast pressure is uniformly distributed on the outer lines of the tunnel face. The tunnel deformations for 30kg TNT blast is analyzed with a peak blast pressure of 6MPa. The blast pressure increases gradually and reaches the peak at 1 millisecond as soon as the blast is initiated. Then it gradually reduces to zero at about 8.2 milliseconds. The 30m longitudinal volume is split into 2 parts - 1m and 29m section; and the blast pressure is applied on the 1m section. The longitudinal effect of 30kg TNT blast will travel more than 20m affecting the tunnel’s twin. Among 30kg, 50kg and 75kg TNT, Bangalore underground metro with lining failed at 75kg TNT. It is noticed that the blast load is absorbed by the soil and the ground surface will be severely affected in case of shallow tunnels. Also, the boundary condition affects the blast pressure for 50 milliseconds only as its effect will not be reflected by the boundary. So, the model boundary is extended for 100m x 50m and its results are tabulated in Table 7. From the analysis and results, it is observed that the tunnel deforms with blast induced pressures while the neighboring tunnel is protected by the lining. In figure 2, the horse-shoe shaped tunnel, (simplified as a circular tunnel in the numerical model) incorporates a safety exit walkway which remains unaffected.

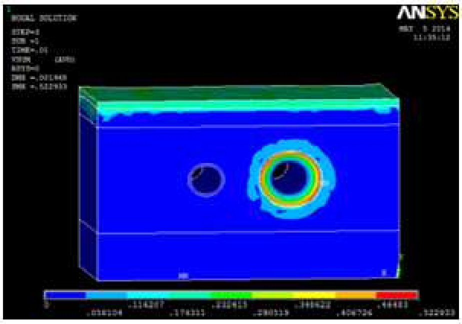
Table 7: Results from Blast Analysis on Twin Tunnel with Lining

RESULTS	0.5 ms	1 ms	9 ms	50 ms
Max. Displacement (m)	0.0078	0.0019	0.0217	0.0098
Velocity (m/s)	0.3065	0.5229	0.6515	0.4857
Acceleration (m/s^2)	74.641	313.213	557.943	112.651

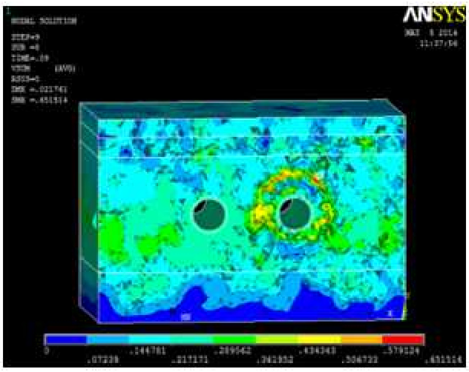
Table 7: Contd.,				
Max. Radial stress (N/m^2)	0.776 x 10^7	0.192 x 10^8	0.639 x 10^7	0.326 x 10^7
Max. Tangential stress (N/m^2)	0.8 x 10^7	0.200 x 10^8	0.435 x 10^7	0.097 x 10^7
Max. Stress intensity (N/m^2)	0.109 x 10^8	0.277 x 10^8	0.450 x 10^7	0.245 x 10^7
Max. Von Mises stress (N/m^2)	0.958 x 10^7	0.244 x 10^8	0.411 x 10^7	0.223 x 10^7

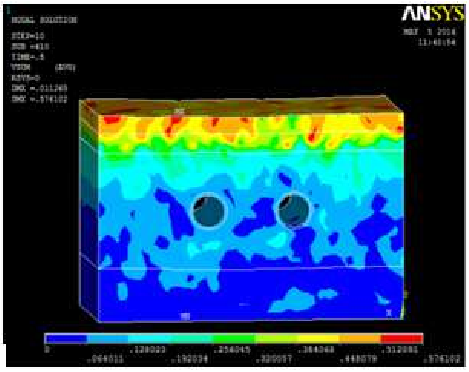
The velocity images shown below in Figure 8, helps in visualizing the twin tunnel with lining under blast loads at various time instances. Also the Von mises stress – Time graph in Figure 9, displays the peak pressure curve at 50 ms time instance.





0.5 ms **1 ms**





9 ms **50 ms**

Figure 8: Velocity Images of Twin Tunnel with Lining at 0.5ms, 1ms, 9ms & 50ms.

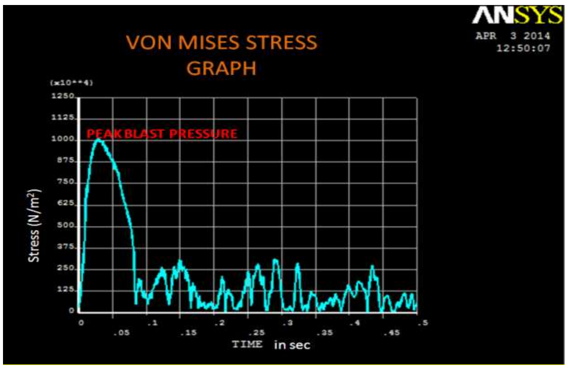


Figure 9:Von Mises Graph for 30kg TNT Blast (for 50 ms)

In order to validate the blast pressures incorporated in the model, the analytical Blast wave without negative phase is compared with the numerical Friedlander Wave derived, as shown in Figure 10 below:

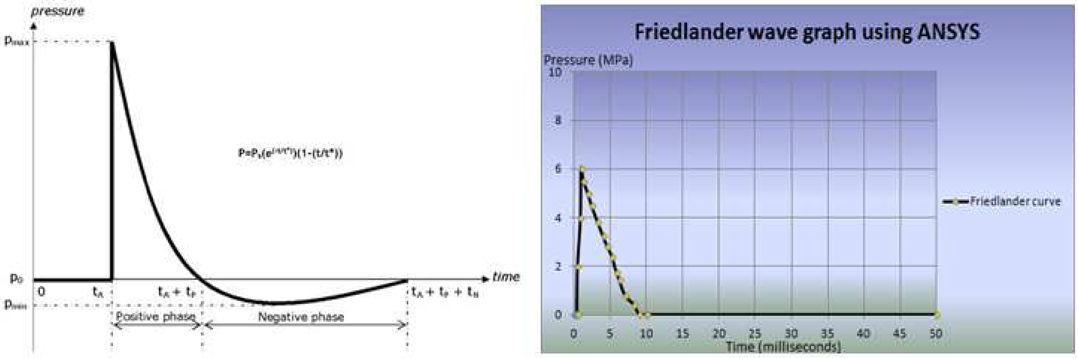


Figure 10: Analytical and Numerical Comparison for Friedlander Wave Equation

CONCLUSIONS AND DISCUSSIONS

A full elasto-plastic non-linear transient analysis is carried out for time instances in milliseconds that reveal the step-by-step deformation of the tunnel. It does not include negative (suction) phase and nonlinearities such as creep and friction which are non-conservative in nature and thus complex to solve. Blast induced pressures due to the explosion may affect the foundation of the nearby buildings if it is a shallow tunnel. The effect of improper boundary conditions may affect the analysis to a great extent. Apart from this, excessive heat may be generated during blasting and the temperature may rise drastically. This may also lead to tunnel failure and should be kept in mind while designing. Finer the meshing, the more accurate will be the results in ANSYS. One of the major limitations of this software is that it takes enormous amount of time to solve a simple geometry for non-linear and blast analysis.

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